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PHYSICAL-MECHANISMS BASED RELIABILITY ANALYSIS FOR
EMERGING TECHNOLOGIES

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PHYSICAL-MECHANISMS BASED RELIABILITY ANALYSIS FOR EMERGING TECHNOLOGIES

Grant FA9550-11-1-0307

A program in support of HiREV

Vanderbilt University

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D. M. Fleetwood, R. A. Reed, and M. L. Alles, Co-PIs**

**Final Report, 2011-2016
April 24, 2017**

Physical Mechanisms Impacting Reliability in Emerging Technologies

1 EXECUTIVE SUMMARY

1.1 Overview

Space and defense systems require the highest levels of functional performance in order to ensure technical superiority for US forces, but at the same time, levels of reliability exceeding those of commercial systems are required. These two requirements are often in conflict, as the most modern and highest performance devices do not have extensive operational histories upon which reliability models can be built. Thus, it is important to develop more predictive reliability models for advanced technologies, based on physical understanding of the failure mechanisms.

The purpose of the research tasks at Vanderbilt in support of the HiREV program is to study failure mechanism in advanced technologies that are of interest to U.S. military and space applications and develop a quantitative understanding of the impact on reliability. The research tasks include reliability issues associated with radiation environments, as well as electrical stress. The goals of the effort are to understand the physical basis of phenomena affecting the reliability of electronic devices; identify key parameters that impact reliability; and provide a forward-looking assessment of reliability challenges for emerging electronic technologies. This work has a great deal of synergy with other basic research efforts at Vanderbilt and is able to leverage the findings of such efforts. This report summarizes the work that has been done during the time period 2011-2016.

1.2 Programmatic Status at Vanderbilt

The period of performance was 9/29/2011-9/30/2016. The work proceeded on schedule and no issues were encountered in the programmatic aspects of the project. The work received a no-cost extension that ended on March 31, 2017.

1.3 Technical Task Areas

This work during this contract period spanned a range of considerations for physics of failure of emerging technologies:

1. Radiation Effects and Reliability in GaN-Based HEMTs
2. Radiation Effects in Ultimately Scaled CMOS
3. Radiation Effects and Reliability in Emerging Memories
4. Combined BTI and radiation effects in advanced dielectrics
5. Mechanisms of hydrogen-related degradation in dielectrics
6. $1/f$ noise & interface traps in SiC MOSFETs

2 Technical Task Results

2.1 Radiation Effects and Reliability in GaN-Based HEMTs

Excellent high-power and high-frequency performance makes gallium nitride (GaN) high-electron mobility transistors (HEMTs)-based microwave power amplifiers. The wide bandgap of GaN provides a very large breakdown field, and the high drain current that these transistors offer makes the broadband matching of monolithic microwave ICs and RF amplifiers simpler and more efficient than for competing technologies. Although the RF performance figures of merit for GaN HEMTs are exceptional, the long-term reliability of these devices is still a concern. For example, stressing a device in the semi-ON condition can result in the generation of defects by hot electrons. This degradation can be caused by a number of mechanisms, often involving dehydrogenation. The defect generation is typically highest at the end of the gate on the gate-drain (G-D) side, where the lateral electric field is at its maximum. This may lead to significant reductions in drain current and transconductance, g_m , as well as shifts in threshold voltage, V_T , resulting in decreased dc, RF, and large-signal performance. High degradation in the semi-ON state can be a concern for devices incorporated in applications such as high-power microwave amplifiers, as the biasing point is close to the semi-ON region. For positive V_{GS} , the drain current decreases with increasing temperature, but the impact on gate leakage is negligible.

As part of this program, GaN/AlGaIn HEMTs fabricated under various growth conditions were stressed under different bias conditions at different temperatures, and the corresponding V_T shift and the g_m degradation were measured. A quantitative model describing this degradation was developed. The shift in V_T and the reduction in g_m are attributed to the creation and/or reconfiguration of defects due to energetic carriers. Only electrons with energies greater than the activation energy can create or reconfigure the defects. The distribution of carriers in energy is obtained using an ensemble Monte Carlo (EMC) approach in a region of the device where the electric field is at its maximum. By combining the model with activation energies obtained from first-principles density functional theory (DFT) calculations, the dominant defects responsible for the observed degradation were identified.

In addition to electrical reliability, degradation of GaN/AlGaIn HEMTs produced by exposure to radiation was examined. The sensitivity to 1.8 MeV proton irradiation is greatly enhanced by biasing the devices during irradiation and/or applying high field stress before irradiation. The resulting defect energy distributions were evaluated after irradiation and/or high field stress via low-frequency noise measurements. Significant increases were observed in acceptor densities for defects with 0.2 and 0.7 eV energy levels. These defects appear to dominate the degradation in threshold voltage and transconductance. Density functional theory calculations show that N vacancy-related defects in GaN and hydrogenated O complexes in AlGaIn are strong candidates for the defects with 0.2 eV energy levels in these devices. We also found that the previously unidentified 0.7 eV defect in GaN is most likely a N anti-site defect (N_{Ga}).

This work is described in detail in the following papers.

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2.2 Radiation Effects in Ultimately Scaled CMOS

As CMOS technology continues to scale, complicated material and design solutions are required to produce reliable devices. For example, gate dielectrics are now typically some form of Hf-based material and various metals are used as the gate electrode. The physical structure has converged on multi-gate or FinFET devices to obtain better electrostatic control of the channel potential. Fully-depleted silicon-on-insulator remains an option, at least for some applications. The choice of channel materials is particularly important, with channel mobility and drive current being the main considerations. Germanium is the leading contender for *p*-channel devices while various compound semiconductors are under consideration for the *n*-channel devices. The overall technology platform, however, is likely to remain silicon-based.

These changes in materials and device structures have important implications for the radiation response of future electronic systems. Possible differences compared to Si technology include charge-generation rates, charge yield, charge-trapping properties, charge collection volumes and transport, and device transient characteristics.

This work has looked at a variety of emerging technologies, with devices and test structures acquired through collaboration with a variety of industrial and university-based researchers, including imec, MIT, Yale, and Purdue. A wide variety of technologies were examined, as well as novel characterization methods.

This work is described in detail in the following papers.

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2.3 Radiation Effects and Reliability in Emerging Memories

Accurate prediction of soft-error rates (SER) for space-borne and ground-based electronics is crucial for quality assurance and mission success. Over-prediction of event rates can lead to unnecessary hardening, affecting system performance. Under-predicting error rates can lead to unreliable system operation. As a fast and relatively simple approach, a single, average value for energy deposition, typically expressed in terms of the effective linear energy transfer (LET) of a given particle type and energy, is often used to compute expected on-orbit error rates in tools such as CREME96.

Previous work reported discrepancies in error rates from differences in track structure and local carrier generation rates of different ion species with similar LETs. It was found that variability in energy deposition is significant for different sensitive volume shapes (e.g., cylindrical, cubic and spherical). This is particularly important for highly scaled technologies, where delta rays may escape the lateral dimensions of the sensitive region, increasing the fluctuations significantly.

As part of this program, we quantified variability in energy deposition associated with the natural statistical fluctuations for identical particles of the same mass and energy using the Monte Carlo Radiative Energy (MRED) code. We found that the naturally occurring variability in energy deposition within a single type of material can lead to lower estimates of soft error rate (SER) than the standard method for computing differential LET flux, which is shown to typically lead to conservative estimates of error rates.

We considered the reliability of resistive memories in particular. Resistive RAM (RRAM) is a possible next generation storage technology due to its scaling, power, and speed advantages. Resistive memory technologies, where bits are stored by changing the resistance of an oxide, have shown promise as non-volatile memories (NVM) for radiation environments due to their total dose tolerance, as well as possible scalability advantages over their planar CMOS counterparts. DRAM, which is also a single transistor storage technology, stores bits as electronic charge across a capacitor. DRAM cells are relatively vulnerable if unhardened, which make way for a NVM that has an inherent reduced level of sensitivity to incident radiation.

A common structure for RRAM storage elements is the one transistor, one resistor (1T1R) memory cell. The 1T1R structure uses a MOSFET connected in series with the resistor to read and write to the memory cell. Single-event upsets (SEUs) in the 1T1R structure

can be caused by charge collection on the access transistor, resulting in a subsequent voltage drop across the resistive element capable of changing the resistor's state (a false write). Using ion- and laser-generated transients, the sensitivity of the RRAM is investigated as a function of the applied voltage, transient characteristics, and location. Simulation models are also presented that can be applied to a variety of RRAM materials and access transistor technology nodes.

RRAM memory cells demonstrate resilience to ionizing dose and displacement damage, despite the presence of a non-hardened access transistor. Degradation in RRAM performance was not observed until large displacement damage doses and complete functionality was regained by cycling. A significant reduction in both the high and low resistance memory states and a complete collapse of the resistive window was observed for large proton fluences in the RRAMs tested. Degradation in resistance states is associated with the generation of additional vacancies, which leads to (an) additional filament(s) in parallel to the existing conductive filament. Additional vacancies from displacement damage in the oxide of the resistive element do not permanently degrade device operation. The low resistance state is recovered to the pre-irradiation resistance through cycling at nominal high-speed switching conditions. Recovery of the resistive window to pre-irradiation values is obtained by applying longer write pulses.

This work is described in detail in the following papers.

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2.4 Combined BTI and Radiation Effects in Advanced Dielectrics

In this work, we measured the low-frequency $1/f$ noise of $\text{Si}_{0.55}\text{Ge}_{0.45}$ pMOSFETs with a Si capping layer and $\text{SiO}_2/\text{HfO}_2/\text{TiN}$ gate stack as a function of frequency, gate voltage, and temperature (100–440 K). The magnitude of the excess drain voltage noise power spectral density (S_{vd}) is unaffected by negative-bias-temperature stress (NBTS) for temperatures below ~ 250 K, but increases significantly at higher temperatures. The noise is described well by the Dutta-Horn model before and after NBTS. The noise at higher measuring temperatures is attributed primarily to oxygen-vacancy and hydrogen-related defects in the SiO_2 and HfO_2 layers. At lower measuring temperatures, the noise also appears to be affected strongly by hydrogen-dopant interactions in the SiGe layer of the device.

This work is described in detail in the following papers.

51. G. X. Duan, E. X. Zhang, C. X. Zhang, J. Hatchtel, D. M. Fleetwood, R. D. Schrimpf, R. A. Reed, S. T. Pantelides, D. Linten, and J. Mitard, "Negative bias temperature instability in $\text{Si}_{0.55}\text{Ge}_{0.45}$ pMOSFETs," in IEEE Semiconductor Interface Specialists Conference, Arlington, VA, 2013.
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2.5 Mechanisms of Hydrogen-Related Degradation in Dielectrics

The formation and annealing of radiation-induced interface traps are of great importance for electronics used in space. The buildup of interface traps varies with irradiation temperature. Understanding this behavior is important for evaluating the radiation hardness of parts that operate at elevated temperatures and in assessing the effectiveness of accelerated test methods. Experiments have also shown that interface-trap creation depends on other parameters like radiation dose rate and ambient hydrogen concentration. Understanding how these conditions combine to affect radiation response is important in predicting device response in various environments.

As part of this program, we identified mechanisms that are likely responsible for interface-trap buildup and annealing at varying temperatures, dose rates, H concentrations, and total doses. At low levels of H₂, proton generation depends on hydrogenated vacancies, but as the H₂ concentration increases, the primary source of protons becomes H dissociation at defects. Protons can be trapped at oxygen vacancies and defects, limiting proton supply near the interface and as a result, interface-trap formation. The effectiveness of this mechanism depends on temperature and proton concentration. At high levels of H₂, and thus proton concentration, this can be significant at room temperature. As H₂ concentration decreases, proton loss at defects becomes significant with increasing temperature. At low dose rates, proton concentrations are lower, so proton loss reactions have little effect. As temperature and H₂ levels increase, the radiation response is dominated by interface-trap passivation, which occurs on the timescale of low dose rate irradiation. At elevated temperatures and H₂ levels, interface traps are passivated by hydrogen on the order of minutes after irradiation. This implies that accelerated tests involving high temperature irradiation are not an accurate comparison to low dose rate irradiation since there are different mechanisms limiting interface-trap buildup. It may be possible to identify a temperature, dose rate, and total dose that are similar to low dose rate degradation, but extensive advance characterization is necessary since the mechanisms are not the same. The model predicts general trends in temperature and dose rate behavior seen in experimental data. Simulations at low dose rates predict that interface-trap buildup at elevated temperatures will be relatively low due to the effects of an enhanced passivation reaction that operates on that time scale, which is only made more effective by the presence of molecular hydrogen.

This work is described in detail in the following papers.

53. D. R. Hughart, R. D. Schrimpf, D. M. Fleetwood, B. R. Tuttle, and S. T. Pantelides, "Mechanisms of interface trap buildup and annealing during elevated temperature irradiation," *IEEE Trans. Nucl. Sci.*, vol. 58, pp. 2930-2936, 2011.
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2.6 1/f Noise & Interface Traps in SiC MOSFETs

This work uses $1/f$ noise as a characterization technique to understand the physical processes involved in limiting the reliability of SiC MOSFETs. For metal films, mobility fluctuations associated with carrier-defect scattering lead to noise. In contrast, for most semiconductor devices, the noise usually results from fluctuations in the number of carriers due to charge exchange between the channel and defects, usually at or near a critical semiconductor/insulator interface. The Dutta-Horn model describes the noise with high precision in most cases. Insight into the physical mechanisms that lead to noise in microelectronic materials and devices has been obtained via total-ionizing-dose irradiation and/or thermal annealing, which is illustrated with several examples. With the assistance of the Dutta-Horn model, measurements of the noise magnitude and temperature and/or voltage dependence of the noise enable estimates of the energy distributions of defects that lead to noise.

This work is described in detail in the following papers.

60. C. X. Zhang, E. X. Zhang, D. M. Fleetwood, R. D. Schrimpf, S. Dhar, S. H. Ryu, X. Shen, and S. T. Pantelides, "Effects of bias on the irradiation and annealing responses of 4H-SiC MOS devices," *IEEE Trans. Nucl. Sci.*, vol. 58, pp. 2925-2929, 2011.
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3 Students completing degrees

Shubhajit Mukherjee

Ph.D.

Defended 10/27/2015

Title: Physical Mechanisms Affecting Hot Carrier-Induced semi-ON State Degradation in Gallium Nitride HEMTs

Jin Chen

Ph.D.

Defended 2/18/2016

Title: Radiation Response and Reliability of High Speed AlGaN/GaN HEMTs

Guoxing Duan

Ph.D.

Defended 12/16/2015

Title: Radiation effects, negative-bias-temperature instability, and low-frequency $1/f$ noise in SiGe/SiO₂/HfO₂ pMOS devices

Kai Ni
Ph.D.
Defended 9/8/2016
Title: Single event transient and total ionizing dose effects on III-V MOSFETs for sub-10 nm node CMOS

Charles Arutt
MSEE
Defended 9/26/14
Title: Protons as a Screen for Displacement Damage in Bipolar Junction Transistors

William (Geoff) Bennett
Ph.D.
Defended 6/23/14
Title: Single Event Upset Mechanisms in Emerging Memory Technologies

Stephanie Weeden-Wright
Ph.D.
Defended 8/21/14
Title: Resistive RAM for Space Applications & the Impact of Scaling Access Circuitry

Kai Ni
MSEE
Defended 7/23/13
Title: A fully embedded Silicon On Insulator Total Ionizing Dose Monitor

Farah El Mamouni
PhD
Defended June 22, 2012
Title: Single-Event-Transient Effects In Sub-70 nm Bulk and SOI FinFETs

Nadia Rezzak
Ph.D.
Defended October 16, 2012
Title: Total Ionizing Dose Effects in Advanced CMOS Technologies

David Hughart
Ph.D.
Defended November 26, 2012
Title: Variations in Radiation Response Due to Hydrogen: Mechanisms of Interface Trap Buildup and Annealing

4 Awards

The following paper was recognized as the Outstanding Student Paper at the 2015 IEEE Nuclear and Space Radiation Effects Conference:

J. Chen, Y. S. Puzyrev, R. Jiang, E. X. Zhang, M. W. McCurdy, D. M. Fleetwood, R. D. Schrimpf, S. T. Pantelides, A. R. Arehart, S. A. Ringel, P. Saunier, and C. Lee, "Effects of applied bias and high field stress on the radiation response of GaN/AlGa_N HEMTs," *IEEE Trans. Nucl. Sci.*, vol. 62, pp. 2423-2430, 2015.

The following paper was recognized as the Outstanding Student Paper at the 2015 GOMAC Conference:

I. K. Samsel, E. X. Zhang, K. Ni, R. A. Reed, R. D. Schrimpf, D. M. Fleetwood, R. A. Weller, M. W. McCurdy, and M. L. Alles, "Physical mechanisms for radiation-induced effects in non-silicon channel CMOS devices," presented at GomacTech, St. Louis, MO, March 23-26, 2015.

The following paper was recognized as the Outstanding Paper at the 2015 Nuclear and Space Radiation Effects Conference. The participation of Robert Reed in this work was supported by this program:

N. A. Dodds, M. J. Martinez, P. E. Dodd, M. R. Shaneyfelt, F. W. Sexton, J. D. Black, D. S. Lee, S. E. Swanson, B. L. Bhuvu, K. M. Warren, R. A. Reed, J. Trippe, B. D. Sierawski, R. A. Weller, N. Mahatme, N. J. Gaspard, T. Assis, R. Austin, S. L. Weeden-Wright, L. W. Massengill, G. Swift, M. Wirthlin, M. Cannon, R. Liu, L. Chen, A. T. Kelly, P. W. Marshall, M. Trinczek, E. W. Blackmore, S. J. Wen, R. Wong, B. Narasimham, J. A. Pellish and H. Puchner, "The contribution of low-energy protons to the total on-orbit SEU rate," *IEEE Trans. Nucl. Sci.*, vol.62, no.6, pp. 2440-2451, Dec. 2015.